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SPECTRUM ANALYSIS OF EASTERLY WAVES IN THE TROPICAL PACIFIC DURING TWO CONTRASTING PERIODS OF SEA-SURFACE TEMPERATURE ANOMALIES

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The structure and properties of the tropical easterly waves have been found to vary considerably between different regimes and time periods. This study investigates the possible roles played by the temporal and spatial sea-surface temperature (SST) variations on the waves. Time series of tropical western Pacific radiosonde data during two contrasting eight-month periods of SST anomalies, May-December 1972, which has abnormally high SST in the central and eastern Pacific, and May-December 1973 which has below normal SST in the same region, are analyzed. In both periods, the waves have the same periodicity of 4-5 days and a lower tropospheric zonal wavelength on the order of 3300 km, but their vertical phase and amplitude distributions as well as the thermal structures are different. The results are discussed in terms of two possible influences the SST variations may have on the waves: 1) direct effect, the warmer SST represents stronger thermal control through cumulus heating; and 2) indirect effect, the variation of SST changes the large-scale mean wind circulation which, in turn, has a strong impact on the wave vertical structure and the relative importance of energy sources other than cumulus heating. Finally, a schematic model of these influences is proposed which may be applied to both the temporal and the spatial variations of SST.

ABSTRACT

The structure and properties of the tropical easterly waves have been found to vary considerably between different regimes and time periods. This study investigates the possible roles played by the temporal and spatial sea-surface temperature (SST) variations on the waves. Time series of tropical western Pacific radiosonde data during two contrasting eight-month periods of SST anomalies, May-December 1972, which has abnormally high SST in the central and eastern Pacific, and May-December 1973 which has below normal SST in the same region, are analyzed. In both periods, the waves have the same periodicity of 4-5 days and a lower tropospheric zonal wavelength on the order of 3300 km, but their vertical phase and amplitude distributions as well as the thermal structures are different. The results are discussed in terms of two possible influences the SST variations may have on the waves: 1) direct effect, the warmer SST represents stronger thermal control through cumulus heating; and 2) indirect effect, the variation of SST changes the large-scale mean wind circulation which, in turn, has a strong impact on the wave vertical structure and the relative importance of energy sources other than cumulus heating. Finally, a schematic model of these influences is proposed which may be applied to both the temporal and the spatial variations of SST.

1. Introduction

Studies on synoptic-scale tropical wave disturbances during the past decade have modified some of the earlier wave models such as those of Riehl (1945, 1954) and Palmer (1952). These studies (Yanai et al., 1968; Nitta and Yanai, 1969; Wallace and Chang, 1969; Chang et al., 1970; Nitta, 1970; Chang, 1970; Wallace, 1971; Reed and Recker, 1971; Burpee, 1972, 1974; Reed and Johnson, 1974; and others), which used primarily the spectrum and/or composite analysis of time series from radiosonde and/or satellite data, are based on many large data samples as compared to the map analysis of the earlier investigations. There are some conclusive agreements among these studies, such as the 4-5 day periodicity and the westward zonal propagation direction. However, quite different results also exist on the wave structure between different studies. The most noticeable discrepancies in the tropical Pacific may be summarized as follows:

1) The vertical phase structure. Studies by Yanai et al. (1968), as well as the earlier easterly wave model by Riehl (1954), indicate a significant eastward tilt of the waves in the lower and middle troposphere; while Wallace and Chang (1970), Chang et al. (1970), Wallace (1971) and Reed and Recker (1971) found most of the waves to have relatively small vertical tilt and those in the western extremity may even tilt westward with height.

2) The thermal structure. Many earlier models suggest that the waves are cold core in nature while more recent studies have frequently indicated a warm core structure in the middle-upper troposphere.

3) The horizontal wavelength. Early synoptic map analyses showed a zonal wavelength of 1500-2000 km. More recently, Yanai et al. (1968) found a wavelength of 6000-8000 km while Wallace and Chang (1969), Chang et al.

(1970) and Reed and Recker (1971) found a wavelength of 3000-4000 km in their studies. Also the wavelength in the upper troposphere has been found to be somewhat longer than that of the lower troposphere.

These discrepancies have been discussed by Wallace (1971) and others. The proposed explanation to date exmphasizes the difference of geographical locations and time periods. For example, the eastern and central Pacific data tend to suggest more eastward phase tilting with height and longer zonal wavelengths than the western Pacific data. The possibility of the existence of two or more types of waves with their relative strength varying from year to year is also mentioned. However, very little physical reasoning has been offered to explain how and why these geographical and annual variations occur with the exception of Holton's (1971) diagnostic numerical model which attributes the different vertical structure to different vertical profiles of the basic-state winds for those waves forced by diabatic heating.

The effects of long-term and geographical variations of sea-surface temperatures (SST) on long-period, planetary-scale atmospheric circulations have been noticed by several authors. Bjerknes (1969) has proposed a relationship between the zonal migration of the Walker circulation over the equatorial Pacific and the SST variations. Kruger and Winston (1974) and Namias (1974) have also identified large-scale circulation fluctuations with the influence of SST changes. Since most of the tropical waves studied earlier were over oceanic regions, it may be interesting to examine whether SST variations account for part of the observed differences in wave structure and properties. Specifically, results of the following test may provide some clue to the validity of this hypothesis. It is well known that the SST in a normal year is cooler over the eastern and central Pacific than over the western Pacific. If the SST variation is indeed responsible for some of the differences of the 4-5 day waves reported by various studies, then one might expect that during a period of warm SST anomalies waves observed at relatively eastern stations should resemble somewhat those normally observed at the western stations, and during a period of cold SST anomalies the reverse should be true.

The purpose of this study is to test such an idea by analyzing the tropical western Pacific radiosonde data over two different periods, the last eight months of 1972 and 1973, during which large and opposite SST anomalies have been noticed, at least in the equatorial eastern and central Pacific region. (Fig. 1 is a comparison of the SST anomalies during these two contrasting periods.) We hope to find out what effects, if any, these variations in SST in the eastern and central Pacific may have had on the structure of the waves in the western Pacific, which is the only region that has a reasonably adequate radiosonde network. These two years were selected also because of their complete satellite coverage. However, the huge amount of raw data to be processed did not enable the National Environmental Satellite Service to make the satellite data available in a suitable form in time for the present study. These satellite data will therefore be analyzed at a later date.

The rationale for studying the relationship between SST and the 4-5 day waves is primarily based on two observations:

1) Some of the waves in the western Pacific have been observed to possess a warm core in the middle troposphere, which implies that latent heating due to cumulus convection may be an important energy source. Cumulus convection is closely controlled by low-level equivalent potential temperature, so the effect of SST is obviously important. On the other

hand, if no substantial differences between the two SST periods is found, important implications for the wave energetics may also be deduced.

2) The change in SST is known to affect the planetary-scale circulation in which the waves are imbedded. Thus the waves may be influenced by SST through the variations in the basic flow.

In this study the results of data analysis will be examined in light of the above considerations.

2. Data

During the periods of interest only data from seven tropical Pacific stations were available from the National Climatic Center. Only six of these stations were found to have a reasonably sufficient number of reports to allow the use of spectrum analysis. These stations are shown in Fig. 2. Twice-daily reports were available at Johnston Island for both years and at Majuro, Ponape, Truk and Koror for 1972, while only once-daily reports were available at Yap for both years and at Majuro, Ponape, Truk, and Koror for 1973. This date set reflects a significant reduction of the tropical Pacific station network as compared to the 1960's and makes it very difficult to calculate kinematic parameters such as divergence and vertical motion, which were included in previous studies (e.g., Wallace, 1971; Reed and Recker, 1971).

At all six stations time series were generated for temperature, zonal and meridional wind components at 13 levels: 1000, 850, 700, 600, 500, 400, 300, 250, 200, 175, 150, 125, 100 mb and for the relative humidity at the six lowest levels. Missing data, which are always less than ~5% of the total series, except for the 150 and 125 mb data at Truk, were linearly interpolated in time. No gap larger than two or three days exists at any of the stations except Johnston Island where the period 19-27 August 1972 was missing. Data at the lower levels was more complete than at the upper levels.

In order to remove long-term trends a Gaussian high-pass filter designed by Holloway (1958) was used. This filter reduces the number of data points from 490 to 404 for the twice-daily series and 245 to 202 for the once-daily series causing 22 days to be lost from either end of each time series. The response function of the filter was such that for periods $\leq$ 20 days the variance response is $\geq$ 95%. The filter has no significant effect on disturbances having the range of periods with which the study is concerned. The UCLA BMD02T program was used for the spectrum and cross-spectrum analyses.

The significance of the spectral results was tested for each power spectrum distribution using a procedure recommended by Mitchell et al. (1966). Since the 4- to 5-day period band is a priori chosen for this study, all power spectra were subjected to a test of the 95% confidence level based on the null hypothesis of simple persistence. Confidence limits for the coherence estimates were also established according to a table prepared by Mitchell (1966) based on data compiled by Amos and Koopmans (1963). The table is entered with the number of degrees of freedom of the coherence estimates given by 1.25 N/m where N is the number of data points and m is the number of lags. For this study N = 404 or 202 and m = 50 or 25,giving a 25 day lag period. The 95% confidence level is equivalent to a requirement of 99.9% or 99.8%, depending on m, for a study that selects a significant frequency band a posteriori.

3. Results

a. Power spectra of individual levels

Power spectral estimates for each of the four parameters, temperature, zonal (u) and meridional (v) wind components and relative humidity were calculated at each of the 13 levels for both years at all six stations.

As expected, the v-spectra at lower levels generally show significant power in the 0.18-0.26 cycle per day (cpd) frequency band (corresponding to a periodicity of ~ 4 to 5 days). The only exception is Johnston Island which is well to the east and north of the five other stations. It is therefore excluded from further study. As an example, the v-spectra at Truk for both periods are shown in Figs. 3-4 with the 95% confidence level indicated only for the 0.18-0.26 cpd frequency band which is considered to be the pre-selected 4-5 day period band. Figs. 3-4 are plotted using a linear frequency scale. Zangvil (1976) has recently proposed that a scale for which the variance is weighted by frequency may be more desirable for presenting spectral diagrams. However, the crucial question in interpreting a power spectral curve is not where the "peak" is (unless a spectral peak is very sharp, in which case most of the plotting methods in use would give the same peaking frequency); but rather is whether the variance satisfies the statistical significance test. If we average the area above and below the 95% limit curve within each spectral window in Figs. 3-4, it can be seen that 19 spectra satisfy the statistical test while 5 do not. (The 150 wnd 125 mb Truk data of 1973 were insufficient for spectral analysis.) Based on this criterion the significant spectra at all five stations for both periods are listed in Table 1. The stations are arranged according to longitude from east to west. The u-spectra are generally less distinct and in both periods only about half at each station satisfy the 95% confidence limit. The temperature and relative humidity spectra are even less significant with the former usually resembling a white-noise spectrum and the latter a red-noise spectrum.

b. <u>Inter-level cross spectra</u>

The vertical structure of the 4-5 day waves was first determined by cross-spectral analysis between levels. The 700 mb and 200 mb levels

Table 1. The 4-5 day v-spectra that satisfy the a priori 95% confidence limit test (indicated by s). A dash indicates missing data.

Station	Period	Level (mb)												
		1000	850	700	600	500	400	300	250	200	175	150	125	100
Majuro	1972	s	s	s	s	s	s	s						
	1973		s	s	s	s	s	s	s	s	s	s	s	s
Ponape	1972	s	s	s	s	s	s	s	s	s	s	s		
	1973		s	s	s	s	s	s	s	s	s		s	s
Truk	1972		s		s	s	s	s	s	s	s	s		
	1973	s	s	s	s	s	s	s	s		s	-	-	s
Yap	1972	s	s	s	s	s	s	s	s	s	s	s	s	s
	1973	s	s	s	s	s	s	s	s	s	s	s		
Koror	1972		s	s	s	s	s	s	s	s	s	s	s	s
	1973	s	s		s	s	s	s	s		s		s	s

were used as the reference levels at each station. The averaged coherence squares and phase differences between the other levels and the base levels for the 0.18-0.26 cpd were computed from the co- and quadrature spectra. We note here that for many cases this frequency band represents a maximum in the coherence squares of the v-component. When the smoothing of the spectral estimates is considered the degrees of freedom for the averaged cross-spectra is found to be ~30, resulting in a minimum significant coherence square of 0.10 for the 95% confidence level in the case of zero background coherence.

Figs. 5-9 display the results for the v-component at the 5 stations. For the 1972 series they show that, almost without exception, the lower levels tend to be out of phase with the upper levels. At every station there is an abrupt phase shift near 300-400 mb, while the levels above and below this demarcation show very little tilt. This "equivalent barotropic" structure is generally absent for the 1973 series at all stations. In this year the two easternmost stations, Majuro and Ponape, show a continuous backward phase tilt below 250 mb with the 700 mb level leading the 250 mb by ~0.6 cycle. Above 250 mb the vertical tilt is quite small. At the next station, Truk, this phase tilt is even stronger and continues all the way up to at least the 175 mb level. The two westernmost stations, Yap and Koror, show a reversed tilt which is somewhat smaller but again continuous from 700 to 300 mb. Above this level the wave axis becomes nearly vertical. Thus the 1973 waves may be characterized by systematic tilt below 250 mb and a continuous, close-to-constant phase above, in sharp contrast with the 1972 results.

c. Spectra of vertically averaged series

The foregoing results led us to attempt a vertical-averaging scheme, similar to that used by Chang et al. (1970), to reduce significantly the number of time series to be analyzed yet still retain the character of the data for most of the individual levels. This was done despite the phase tilts in 1973 because the design of the scheme is such that the phase difference between levels to be averaged is always < 1/5 of a cycle. Table 2 outlines this scheme. The wind components were divided between two layers which are of opposite phase in 1972 and were averaged within each layer. The three series, T_1, T_2 and T_3, represent the temperature near the tropopause, between the two layers, and near the surface, respectively. Relative humidities were averaged for the 700-400 mb layer because Wallace (1971) and Gray _et al_. (1975) have found that fluctuations in the humidity data are much more pronounced above 700 mb.

The power spectra for all layer quantities were calculated for both years but are not shown here. As was expected the v_L and v_H spectra are characterized by significant variance in the 4-5 day period at all stations for both periods. Related significant variance for u_H becomes apparent at all stations in 1972 and at all stations except Truk in 1973. There is some evidence of related significant variance in u_L spectra, especially in 1973; but most of the power is found in the lower frequencies near 0.1 cpd. It is also noted that more prominent spectral peaks of the 1973 v_H series also exist at somewhat lower frequencies centered around 7-10 days, and sometimes these peaks cover a wide band which include the 4-5 day periods. The power spectra for RH again resembles that of a red noise and those for T are again generally quite flat.

d. Inter-station cross spectra

For both years only the v_L and v_H inter-station cross spectra were computed. The results for the 0.18-0.26 cpd band are presented in Figs. 10 and 11 as phase-difference vs longitudinal difference between stations.

Table 2. Scheme for vertical averaging

Parameter	Symbol	Levels Averaged
Meridional wind component (lower levels)	v_L	1000*,850,700,600 mb
Meridional wind component (upper levels)	v_H	300,250,200,175,150,125 mb
Zonal wind component (lower levels)	u_L	1000,850,700,600 mb
Zonal wind component (upper levels)	u_H	300,250,200,175,150,125 mb
Temperature	T_3	1000,850 mb
	T_2	300 mb
	T_1	125-100 mb
Relative humidity	RH	700,600,500,400 mb

*At Truk the 1000 mb v of 1973 is excluded in order to keep the phase difference between levels averaged < 1/5 cycle.

For each pair of stations the eastern station was used as the base series. It is apparent that the waves propagate westward in both layers during both periods. The wavelengths for the wave disturbances are estimated by the intersection of the best-fitting line of the points with significant coherence squares and the unit cycle phase line. For both periods the lower tropospheric wavelength is seen to be ~3300 km, which is in good agreement with the results of Wallace and Chang (1969), and slightly less than those reported by Chang et al. (1970) and Reed and Recker (1972). The upper tropospheric wavelengths are, on the other hand, ~3600 km for 1972 and ~4200 km for 1973.

e. Inter-parameter cross spectra

Cross spectra were computed between the vertically-averaged layer quantities to determine the three-dimensional structure of the 4-5 day waves. The results as tabulated in Table 3 for 1972 and Table 4 for 1973 may be summarized as follows:

1) The relationships between wind components. The phase difference between v_L and v_H, as expected, is 1/3 - 1/2 cycle in 1972. For 1973 they are typically closer to 1/3 cycle. However, the interpretation of the 1973 results is quite different from that of the 1972 period because of the continuous phase propagation into the middle-upper levels shown by the inter-level cross spectra. The u_L and v_L series generally have a significant in-phase correlation in 1972 which indicates a NE-SW horizontal tilt; but for 1973 this relationship is much less definitive. The v_H-u_H phase relationship, on the other hand, indicates the NE-SW tilt during both periods whenever the coherence is significant.

2) The relationships between meridional winds and temperature. In 1972 v_L generally lags T_2 (middle-level temperature) by ~1/3 cycle and

Table 3. Inter-parameter cross spectra for the 0.18-0.26 cpd for 1972.

a. Coherence square in hundredths. Confidence level ≥ 95% if coherence square ≥ 0.10.

Station	Base series v_L					Base series v_H			Base series T_3		
	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	13	08	27	20	18	05	26	08	26	28	15
Ponape	12	42	06	10	15	13	07	06	21	09	05
Truk	07	45	24	02	02	24	02	12	02	11	13
Yap	18	14	11	15	11	09	30	03	11	05	15
Koror	15	21	18	10	03	02	34	18	14	16	27

b. Phase difference in hundredths of a cycle. Positive values indicate that the base series leads the other series.

Station	Base series v_L					Base series v_H			Base series T_3		
	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	-30	-	-21	34	11	-	-24	-	50	-22	47
Ponape	-41	04	-	17	08	-06	-	-	36	-	-
Truk	-	00	-38	-	-	-12	-	40	-	-14	-33
Yap	-40	07	-43	20	-31	-	-21	-	-45	-	46
Koror	50	05	-26	23	-	-	-22	46	-41	-09	50

Table 4. Same as Table 3 except for 1973.

a. Coherence square in hundredths.

Station	Base series v_L					Base series v_H			Base series T_3		
	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	10	07	16	19	10	06	15	07	13	14	40
Ponape	17	22	09	07	15	19	26	14	09	04	11
Truk	21	05	08	07	12	14	22	06	07	08	15
Yap	19	12	04	05	03	18	19	08	14	16	34
Koror	34	13	04	21	21	09	14	10	03	19	28

b. Phase difference in hundredths of a cycle.

Station	Base series v_L					Base series v_H			Base series T_3		
	v_H	u_L	T_2	T_3	RH	u_H	T_1	T_2	T_2	T_1	RH
Majuro	-42	-	-35	18	-18	-	-25	-	31	-06	46
Ponape	-35	37	-	-	04	-12	-12	40	-	-	43
Truk	-35	-	-	-	03	-10	-21	-	-	-	-36
Yap	-24	04	-	-	-	-09	-23	-	40	04	49
Koror	-31	-17	-	05	-27	-	44	15	-	-10	-43

leads T_3 (low-level temperature) by ~1/4 - 1/3 cycle. This is in excellent agreement with the results of Chang et al. (1970). It can thus be inferred that the troughs are cold near the surface and are capped by warm temperature anomalies in the middle-upper levels. Direct cross spectra also indicate that T_3 is out of phase with T_2 while it tends to be in phase with T_1. So near the tropopause the temperature above the lower layer trough is cold. This thermal structure plus the out-of-phase relationship between lower and upper layer v are in agreement with the gradient wind relationship and indicate that the 1972 waves are equivalent barotropic in nature. This relationship also checks out well with the result that v_H lags T_1 by 1/4 cycle. In 1973 most of the v_L-T_2, v_L-T_3 coherences are quite low and the few significant phase relationships are inconsistent, although the phase reversal between T_1 and T_2, and T_2 and T_3, are still evident and v_H again lags T_1 by ~1/4 cycle at every station except Koror.

3) The relationships between meridional winds and relative humidity. Somewhat surprisingly, the phase between v_L and RH varies widely in 1972. Among the three stations that have significant coherences, Majuro and Ponape show maximum RH slightly to the east of maximum v_L, or in the western end of the ridge area. Only Yap has maximum RH in the trough which is what might be expected from the thermal structure in terms of latent heat release, based on Chang et al.'s (1970) findings. For 1973 the results are also inconclusive that at Majuro and Koror the RH maxima are in the troughs while at Ponape and Truk they are in phase with maximum v_L. In both periods the RH-T_3 show a very significant out-of-phase relationship and for 1972 this is inconsistent with those cases where maximum RH is not in phase with trough. No good explanation can be offered for these diverse results. However, because RH is temperature dependent, perhaps specific humidity should be used in place of it in future studies.

4. Discussion

The spectrally determined wave structures of the last eight months of 1972 and 1973 at the five western Pacific stations show some similarities between the two years as well as some differences. The main similarities are:

1) The 4-5 day periodicity is significant at all stations.

2) The wavelengths are close to 3300 km in the lower troposphere.

3) A general out-of phase relationship exists between low-level (1000-600 mb) and high-level (above 300 mb) v-components.

The main differences between the two periods are:

1) The 1972 waves show an abrupt phase shift ~180° at about the 300-400 mb layer. This is contrasted with a continuous phase tilt with height in 1973 during which the waves at the easternmost stations, Majuro, Ponape and Truk, have a substantial eastward tilt in the lower and middle troposphere; while those at the western stations, Koror and Yap, tilt westward with height.

2) The thermal structure of the 1972 waves is well defined with a warm core in the middle troposphere, whereas in 1973 it is quite poorly defined.

3) As depicted in Fig. 12, the amplitude of the low level waves (below ~300 mb) deduced from variance is everywhere higher in the 1972 period than in 1973. Above ~300 mb there is no systematic difference between the two periods.

In the introduction a specific test was designed for the hypothesis of attributing the spatial and temporal variations of the 4-5 day wave structure to the variation of SST. Since the earlier spectral studies reviewed by Wallace (1971) and a detailed composite study by Reed and Recker (1971) have all shown that waves at the relatively eastern stations of the central and western Pacific network, such as Canton Island and Majuro, usually possess a strong backward tilt with height; and those at the relatively western stations, such as Ponape, Truk, Yap and Koror, usually show a virtually equivalent-barotropic, warm-core structure; the results of our test must be viewed as quite positive. This follows because during the warm anomaly of 1972, waves at all stations including Majuro resemble the normal "western station" waves; and during the cold anomaly of 1973 all stations including Ponape to Koror have a systematic and continuous phase tilt and resembles the normal "eastern station" waves. The reversed tilt at Yap and Koror should not be considered as a significant discrepancy because the vertical shear of the time-mean zonal flow (Fig. 14) at these two stations is opposite to that at the other stations within the layer of the phase tilt.

The lack of vertical tilt and the better-defined thermal structure in 1972 suggests that the waves are more dominated by the "warm-core" energetics in this year. This seems to be a direct effect of the warmer SST which favors cumulus convection and latent heating. Due to the prominence of this energy source one may expect that the waves would be more active in 1972. This is indeed the case at the lower and middle levels below 300 mb. It may be due to this larger wave amplitude at the lower levels that the year of 1972 had a very active typhoon season (based on the CISK theory which emphasizes the importance of low-level convergence). We would also like to point out here that the studies summarized by Wallace (1971) also indicate that usually the low-level wave amplitudes at the westernmost stations of Koror and Yap are larger than those at the eastern stations. Thus the amplitude variation in the lower troposphere between the two periods is again consistent with the positive result of our test mentioned earlier.

The structure of the waves may also be influenced by the basic-state zonal flow. Figs. 13-14 are the longitude-height sections of the eight-month mean zonal wind in the two periods. It is evident that much stronger westerly shear in the vertical exists in 1973. This appears to be related to the position and intensity of the zonal Walker circulation due to the cold SST anomalies in the eastern Pacific. The differences in the mean flow patterns are most pronounced in the upper troposphere. Using a linearized, numerical diagnostic model to study equatorial waves forced by cumulus heating, Holton (1971) showed that vertical shear of the zonal mean wind has an important effect in the wave structure. A comparison of our results with those of his model thus seem appropriate if we assume that the waves in both years are maintained by deep cumulus heating and that they adjust to the local time-mean winds rather quickly.

The three easternmost stations, Majuro, Ponape and Truk, have strong eastward phase tilt from lower to upper troposphere in 1973. This is consistent with Holton's (1971) calculations for a strong vertical westerly shear of mean zonal wind with height. At Yap and Koror both years have weak easterly shear in the lower troposphere and the waves tilt slightly westward with height. This is again in agreement with Holton (1971); however, the 1973 shear is even weaker than in 1972, while the phase tilt is more extensive. An explanation for this apparent paradox is that the 1972 waves are much more convectively controlled, as indicated by the warm core structure. It is reasonable then to expect that such waves have less vertical tilt.

In Holton's (1971) model the amplitude of the diabatic heating is fixed for all zonal wind profiles he considered. The low-level v-amplitude associated with vertical shear generally shows a slight increase over that of the no-shear case, and the ratio of the upper tropospheric amplitude maximum to that of the lower troposphere is generally smaller. On the other hand, our spectral results show that the 1973 v-amplitude at upper levels is comparable to that of 1972 despite its relative smallness at the lower levels. These results thus may be indicative of the presence of energy sources other than condensation heating. Among the possibilities are dynamic instability and mid-latitude forcing. The strong westerlies over the eastern stations suggest that the tropical upper tropospheric trough (TUTT) may be extended equatorward from its usual position in the Pacific. Sadler (1967) and others have found that upper-level synoptic-scale disturbances tend to develop along TUTT, and dynamic instability has been proposed as a possible mechanism (Krishnamurti, 1971; and Colton, 1973). Classical wave theories (Charney and Drazin, 1961; Charney, 1969; Bennet and Young, 1971) also suggest that mid-latitude forcing is more efficient when the zonal mean flow is more westerly. It is therefore quite conceivable for one or both of these mechanisms to act as a major energy source for the 1973 waves, mainly at the upper levels which show a wide spectral band of variance including the 7-10 day and the 4-5 day bands. If this is the case then the energetics of the 1973 waves would be quite different from the 1972 waves. The reason that Holton's (1971) vertical phase results still seem to apply may be due to the fact that the maximum heating in his model occurs at the 300 mb level which might be looked upon as a parameterization of some arbitrary upper-tropospheric energy source, not necessarily an exclusive representation of the cumulus heating only. If we now assume that the 4-5 day waves in 1973 can be viewed as internal waves as was treated in Holton's model, the easterly maximum of the mean zonal wind in the lower troposphere in 1973 may then serve as a "quasi-critical" level with small Doppler-shifted frequency and attenuate the downward wave energy propagation by viscous damping (Lindzen, 1971).

The very quiet typhoon season of 1973 may be due to a combination of two factors. The cold SST's certainly are unfavorable for warm core development. In addition, the strong vertical wind shear, which is itself a consequence of the SST distribution, tends to suppress tropical storm development due to the ventilation effect (Gray, 1975). Another observation worth mentioning is that the estimated wavelengths in both upper and lower troposphere during both periods are close to 3000-4000 km. This indicates that the presence of a strong vertical phase tilt does not itself dictate the existence of a different type of wave disturbance with a longer wavelength on the order of 8000 km, as was suggested by Wallace (1971).

5. Conclusions

The above discussion suggests that the two possible effects of SST variations on waves mentioned in the introduction, namely the direct control of cumulus heating as an energy source and the indirect influence through planetary-scale circulation changes, are both present. These effects are summarized schematically in Fig. 15. The top panel (Fig. 15a) represents a warm SST anomaly period in the eastern and central Pacific and the bottom panel represents a cold SST anomaly period in the same region. The zonally-migrating, SST-controlled Walker circulation is shown along with the low and upper-level mean zonal winds observed in 1972 and 1973. The imbedded 4-5 day wave chain, with its streamline ridge and trough positions at a given time plotted, has a zonal wavelength of 3000 km. During a warm anomaly the waves are equivalent barotropic dominated by warm core energetics throughout the domain. A very slight westward tilt of the low-level wave axis is indicated for the westernmost region of the western Pacific which is, presumably, a result of the strong easterly vertical shear of the mean zonal wind. During the cold anomaly the influence of the vertical shear is much stronger and the thermal control of the wave structure is much weaker. The associated temperature fluctuations at the middle level and near the surface are based on hydrostatic consideration only. The italicized *r* and *t* symbols indicate that the lower tropospheric wave amplitude is smaller than that of a warm anomaly period. The somewhat longer averaged zonal wavelength in the upper troposphere estimated by the cross-spectral analysis, especially for 1973, may now be interpreted as due to the changing vertical phase tilt of the waves.

The structures described in Fig. 15 imply that, at least during a cold anomaly period, the waves are fairly "linear" with respect to the changing vertical shear in the sense that they do not have a strong memory of their phase structure as they propagate through a varying medium and very quickly adjust to the local condition. But the SST variation in the "upstream" (with respect to phase propagation of the waves) region may exercise a direct influence in their energetics. Due to our present inability of obtaining adequate SST data in the tropical western Pacific during 1972-1973, we offer three possible interpretations for the cause of this influence:

1) The prevailing easterly winds over the central and eastern Pacific transport the thermodynamic properties (which may be identified with a characteristic equivalent potential temperature) of the upstream low-level air westward; which, in turn, affect the degree of conditional instability in the central and sometimes western (during the cold anomaly) Pacific.

2) During the warm anomaly the CISK mechanism has already been activated while a wave is in the upstream region, so that it continues to operate downstream with large-enough low-level amplitude for lifting. During the cold anomaly waves moving into the western Pacific have smaller low-level amplitudes and therefore making it more difficult to release CISK.

(The above two may apply if the western Pacific SST remains normal during both anomaly periods.)

3) The SST anomalies as shown by the eastern and central Pacific data in Fig. 1 extend westward into the western Pacific.

It is quite possible that more than one or all three of these interpretations are valid.

Fig. 15 may also be applied to a normal SST year. In such case waves in the eastern and central Pacific (perhaps including Majuro) will assume the structure of those waves east of the ascending branch of the Walker circulation during the cold anomaly (Fig. 15b),and the western Pacific waves will assume the structure of the waves during the warm anomaly (Fig. 15a).

After the completion of this study, a 1972-1973 satellite visible and infrared data set in the form of tropical mercator pictures became available to us. A composite study using this data to compare the relationships between the organized convective cloud field and the 4-5 day waves during the two contrasting periods is currently being planned at the Naval Postgraduate School. We hope that such a study would shed further light on the question of the wave energetics during the two periods. In any case our conclusions are subject to re-examination and refinement until a larger sample of contrasting SST periods can be studied.

Finally, we would like to mention a related interesting scientific question regarding the control of planetary scale circulations and SST variations. In this paper we have consistently referred to the difference between the time-mean zonal wind of the two contrasting periods as due to the variation of the Walker circulation. We feel this is at least partially justified in view of the zonal migration of the ascending branch which is consistent with the eastern Pacific SST variations. On the other hand, Krishnamurti (1971) has shown that the Walker circulation may be only one part of the vigorous east-west circulation due to mainly the differential monsoon heating during northern summer, and the development of the Pacific TUTT may be viewed as a thermodynamic and dynamic consequence of this east-west monsoon circulation (see also Krishnamurti et al., 1973). The interaction of the east-west monsoon circulation and the Walker circulation thus seems to be an important problem for studying the tropical planetary scale motions. This problem also has a particularly intriguing aspect because the monsoonal heating has a well defined annual cycle while the time scale of the SST variation is distinctly different. In the schematic diagrams of Fig. 15, one may interpret the upper level easterlies shown by the velocity vectors as due to the upper-level monsoon anticyclone centered near Tibet, and that in the cold anomaly year of 1973 (Fig. 15b) the Walker circulation effectively destroys these tropical easterlies in the western Pacific. If the Walker circulation indeed exercises such a substantial influence then the study of the summer monsoon and its associated synoptic-scale disturbances (which, in our view, include the 4-5 day tropical easterly waves) could become even more complicated.

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FIGURE LEGENDS

Fig. 1. Mean sea-surface temperature anomalies (°F, 2°F = 1.1°C) of the eastern Pacific for May-December 1972 (a), and May-December 1973 (b). The values are departures from the 1948-1967 20-year mean of the same eight-month period. Shaded area indicates warm anomaly. (Data based on Fishing Information, Southwest Fisheries Center, National Marine Fisheries Service/NOAA, La Jolla).

Fig. 2. Radiosonde stations used in this study.

Fig. 3. Power spectra ($m^2 sec^{-2}$ per $2\pi/50$ day^{-1}) at the individual pressure levels of Truk for the May-December 1972 period. The 95% confidence limit (dashed line) is plotted in the 0.18-0.26 cpd frequency band.

Fig. 4. Same as Fig. 3 except for 1973.

Fig. 5. Vertical phase differences in cycles of the 0.18-0.26 cpd band for the v-series at Majuro. The circles are for base series at 700 mb and the crosses for base series at 200 mb. The associated numbers are coherence squares in hundredths. Only values satisfying the 95% confidence level are included.

Fig. 6. Same as Fig. 5 except for Ponape.

Fig. 7. Same as Fig. 5 except for Truk.

Fig. 8. Same as Fig. 5 except for Yap.

Fig. 9. Same as Fig. 5 except for Koror.

Fig. 10. Phase difference in cycles of the 0.18-0.26 cpd band for v_H(top) and v_L(bottom) as a function of the longitudinal difference between two stations for May-December 1972. The crosses indicate the associated coherence squares (included in parentheses in hundredths) satisfy the 95% confidence level. Data are labeled with the identifiers (M: Majuro, P: Ponape, etc.) for the station pair involved with the first station as the base series.

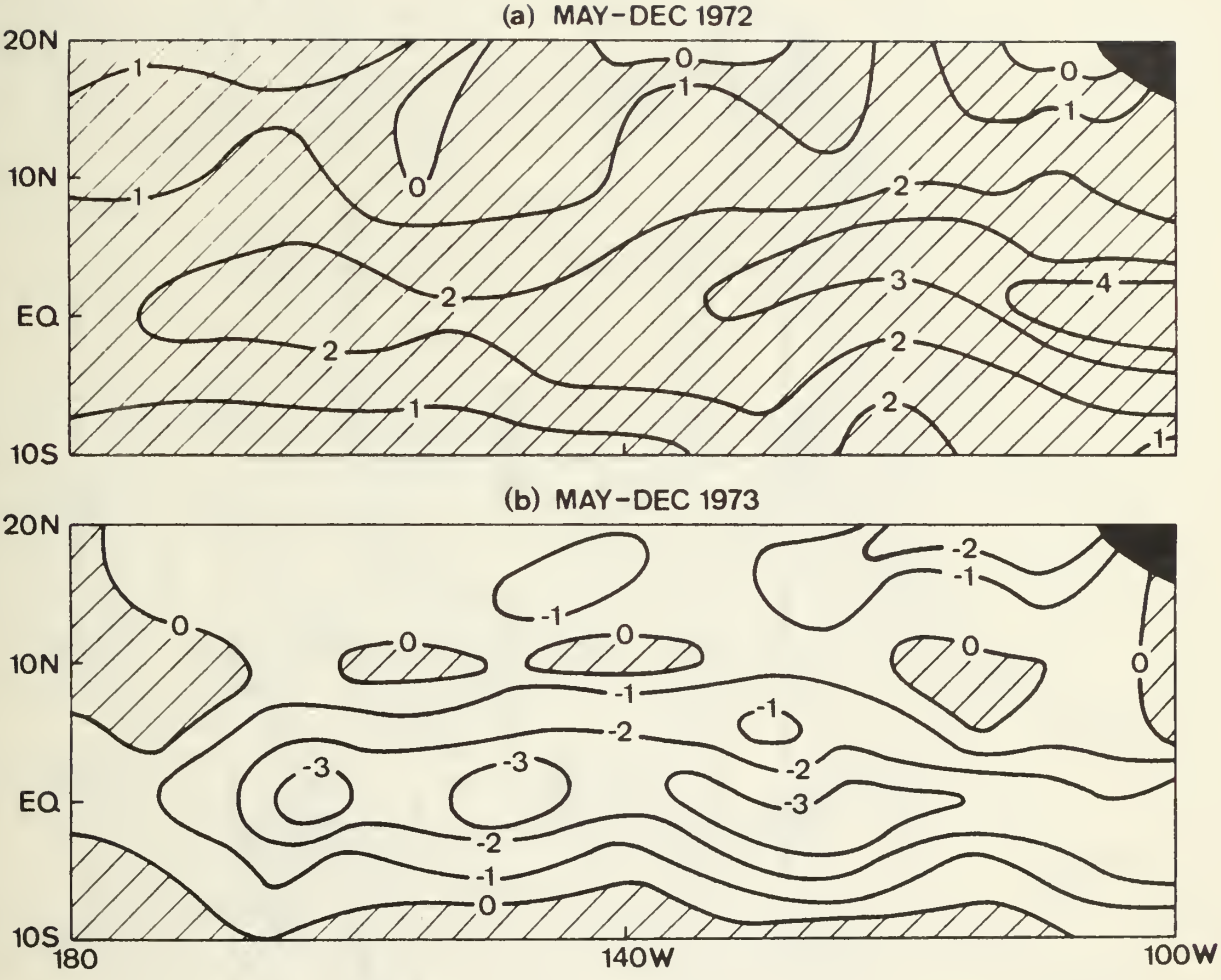
Fig. 11. Same as Fig. 10 except for 1973.

Fig. 12. Vertical amplitude distribution for the 0.18-0.26 cpd band at the five stations for May-December 1972 (solid lines) and May-December 1973 (dashed lines).

Fig. 13. Longitude-height cross section of the mean zonal winds for May-December 1972.

Fig. 14. Same as Fig. 13 except for 1973.

Fig. 15. Proposed model for the influence of sea-surface temperature variations on the 4-5 day wave structure. See text for details.



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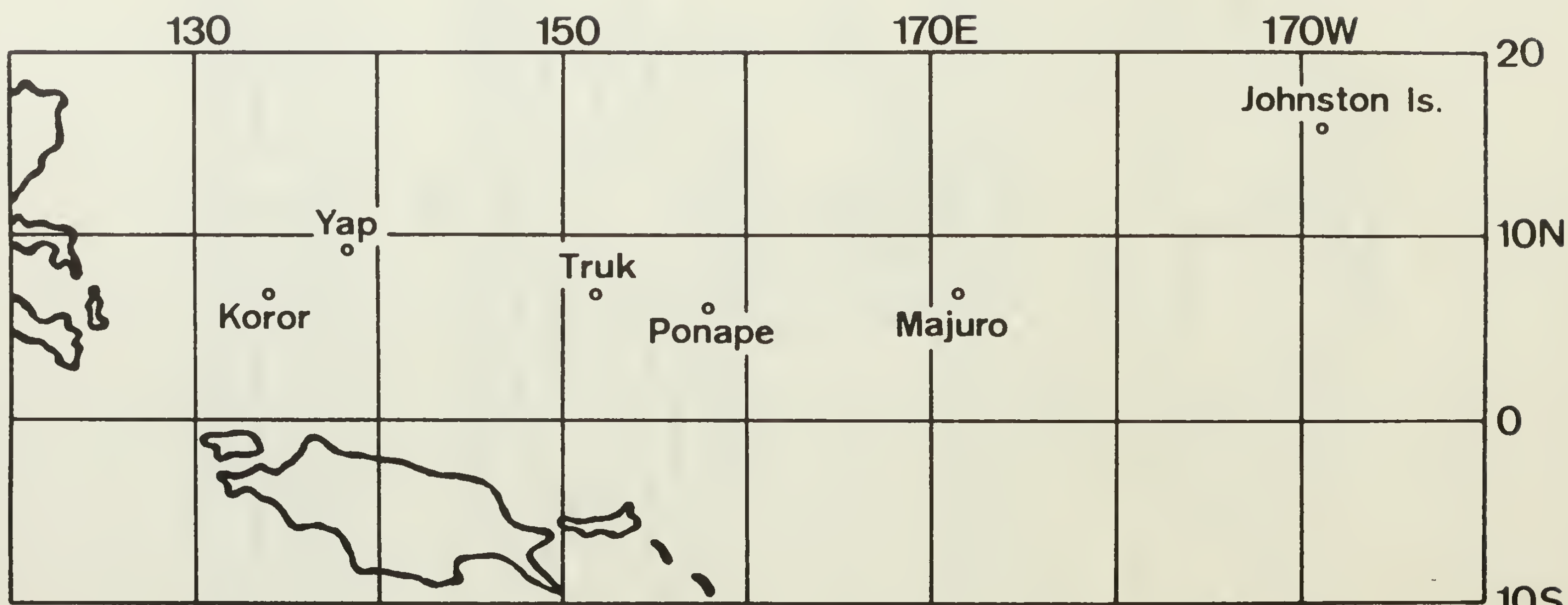

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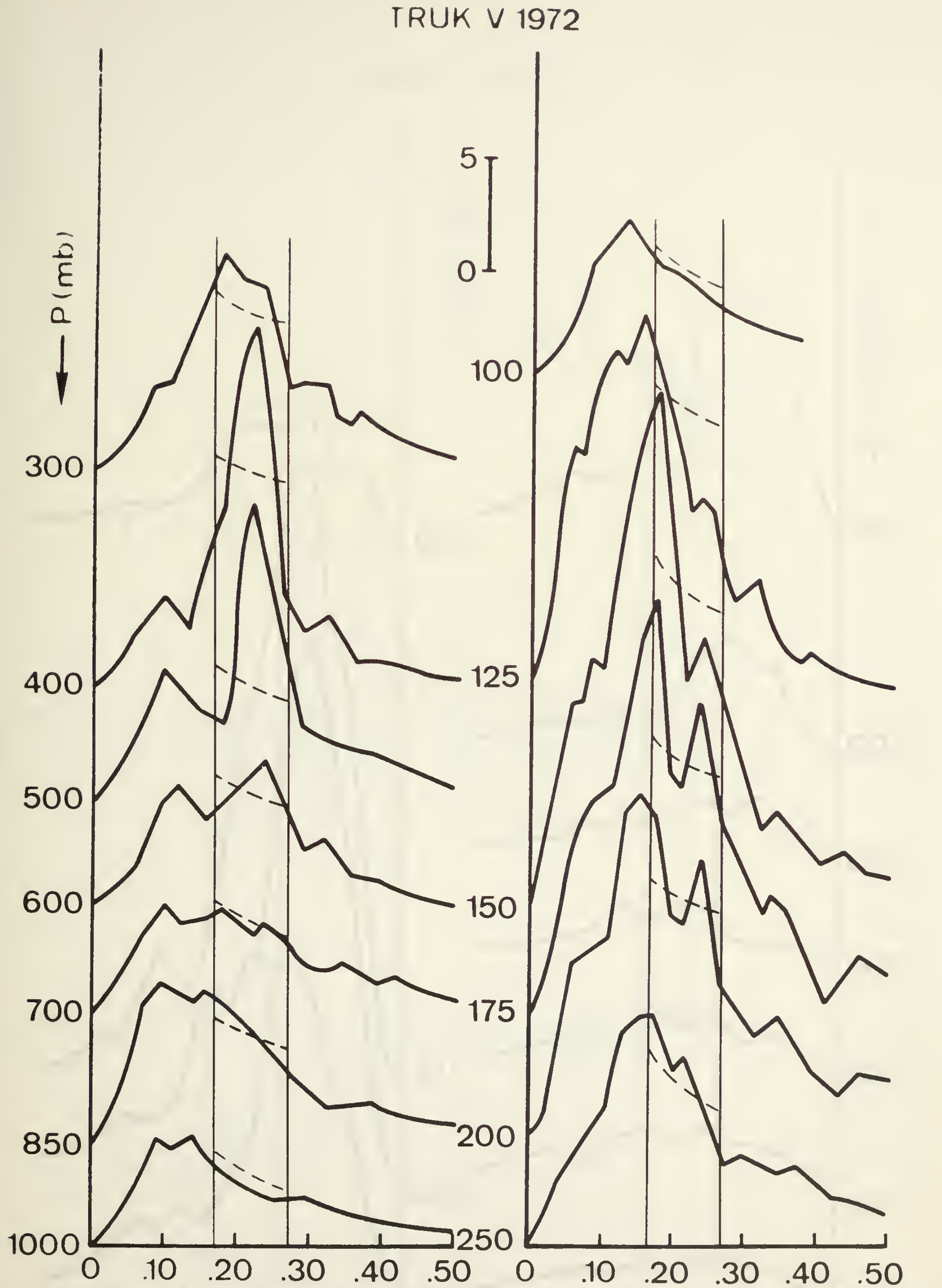

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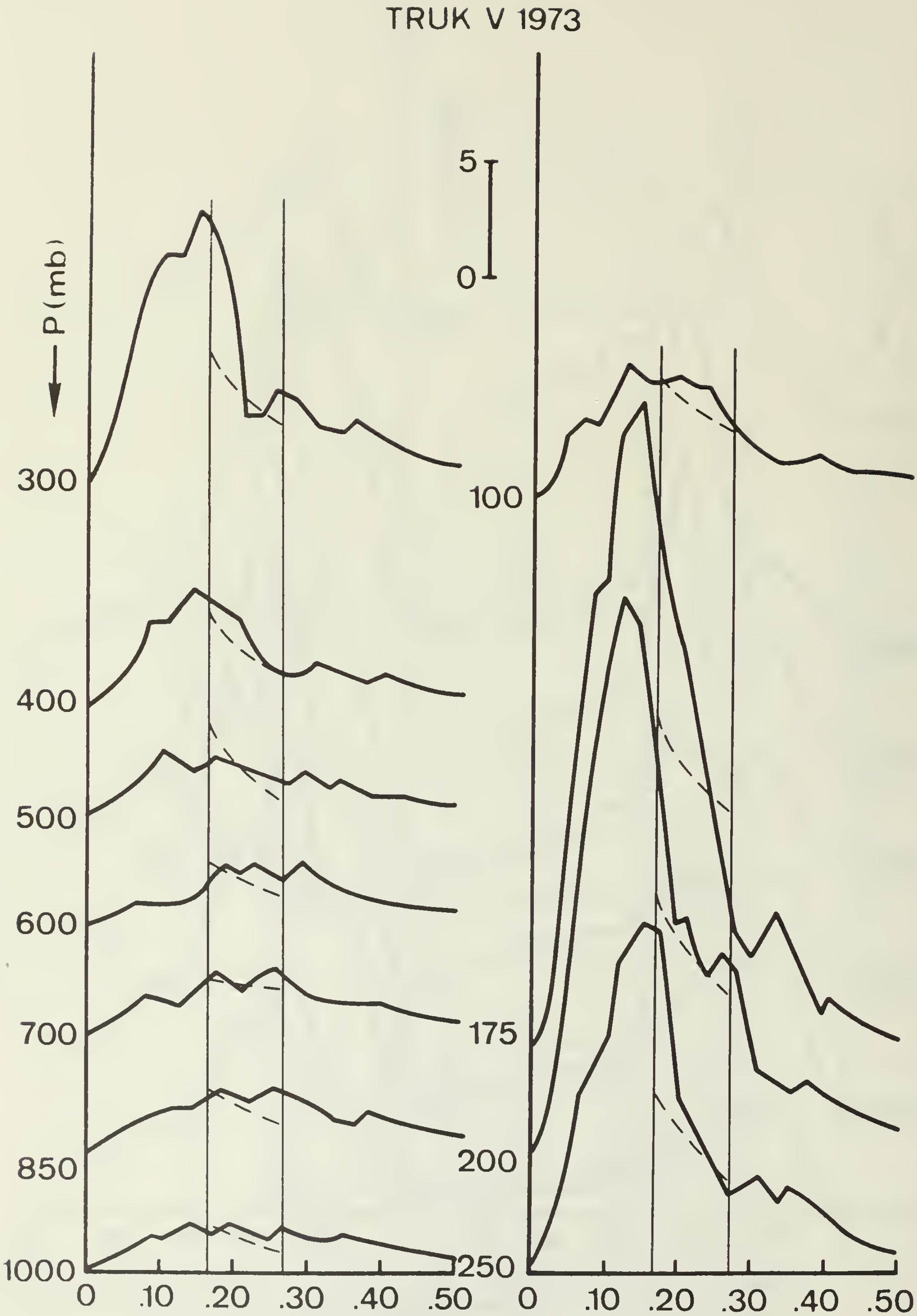

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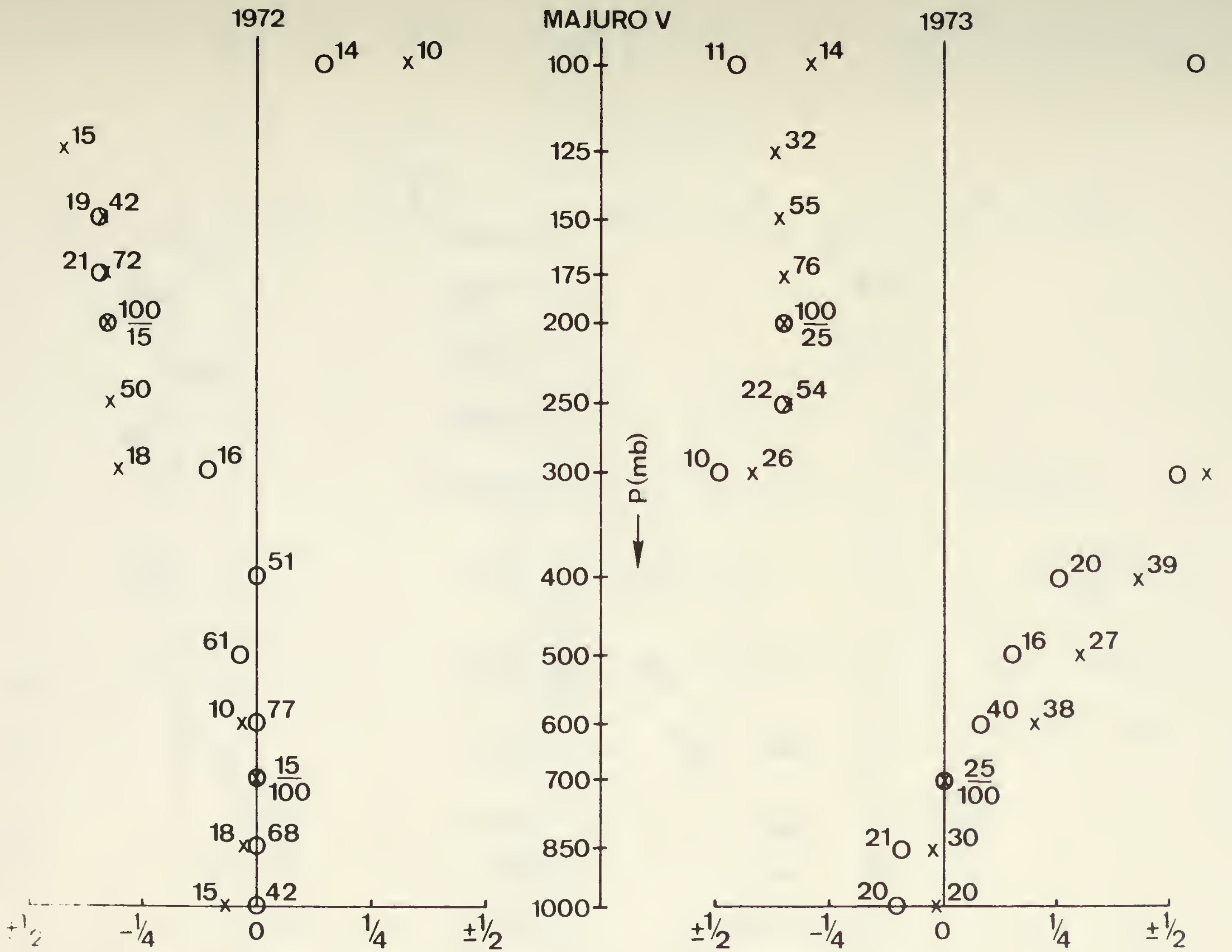

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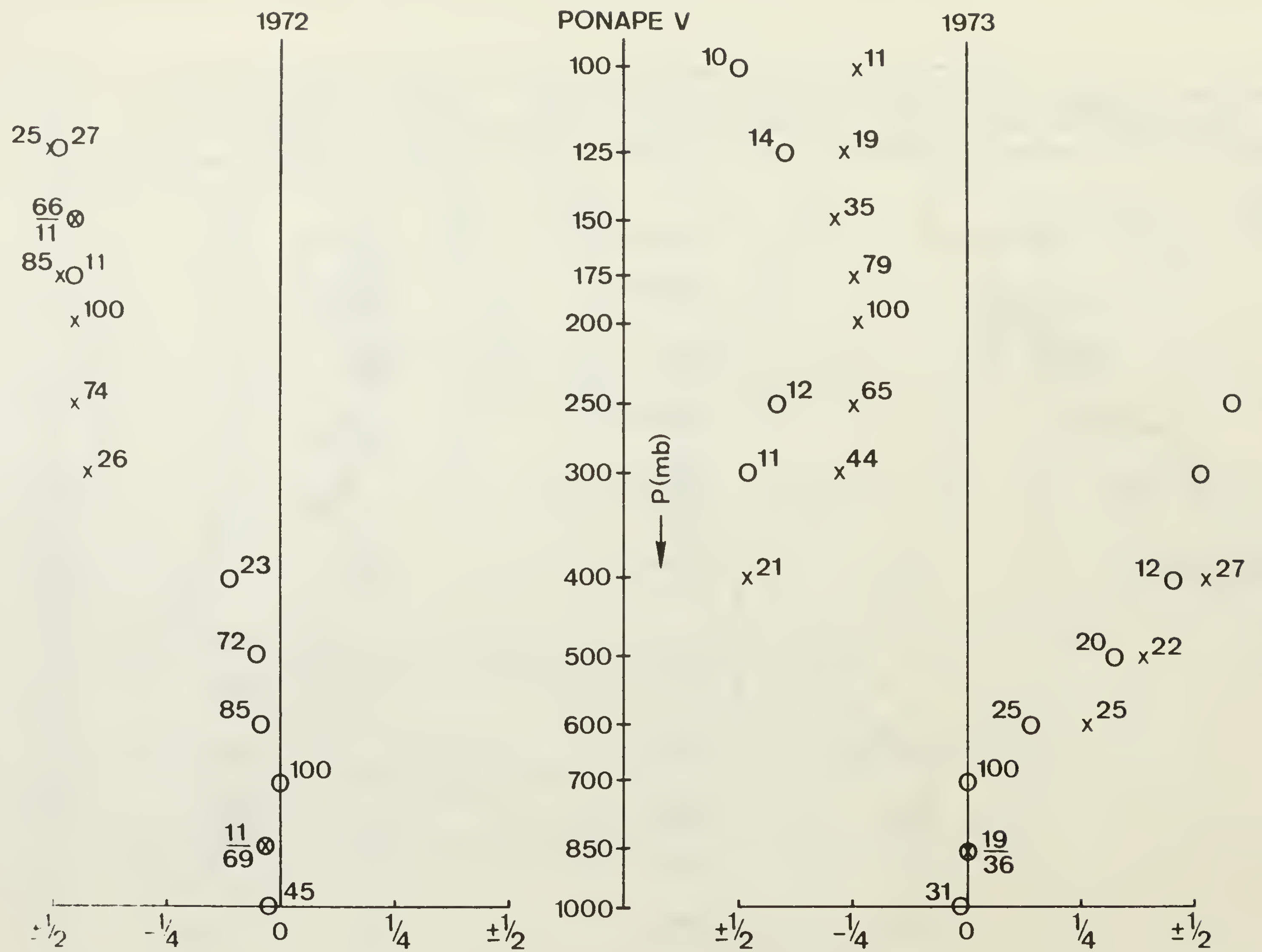

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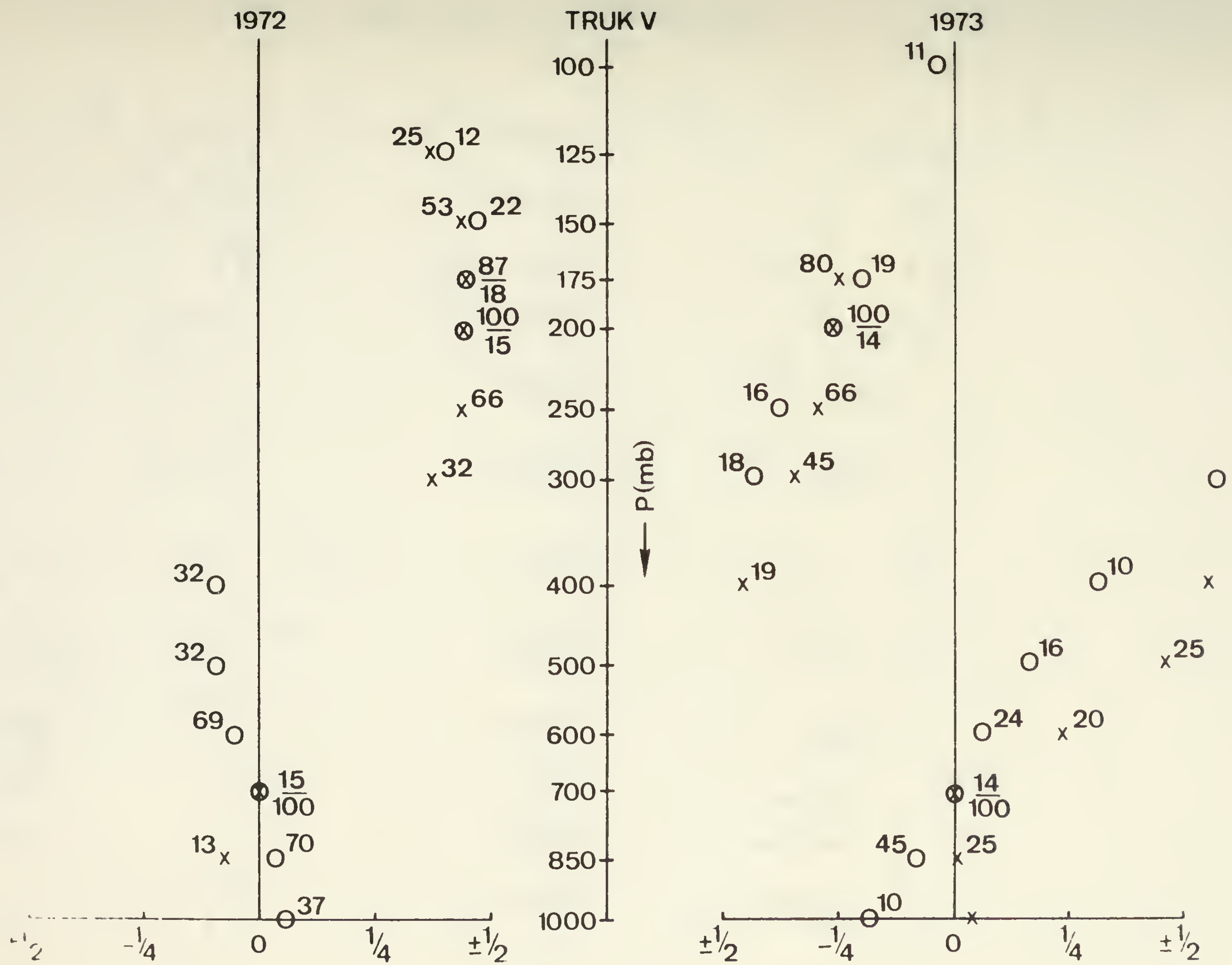

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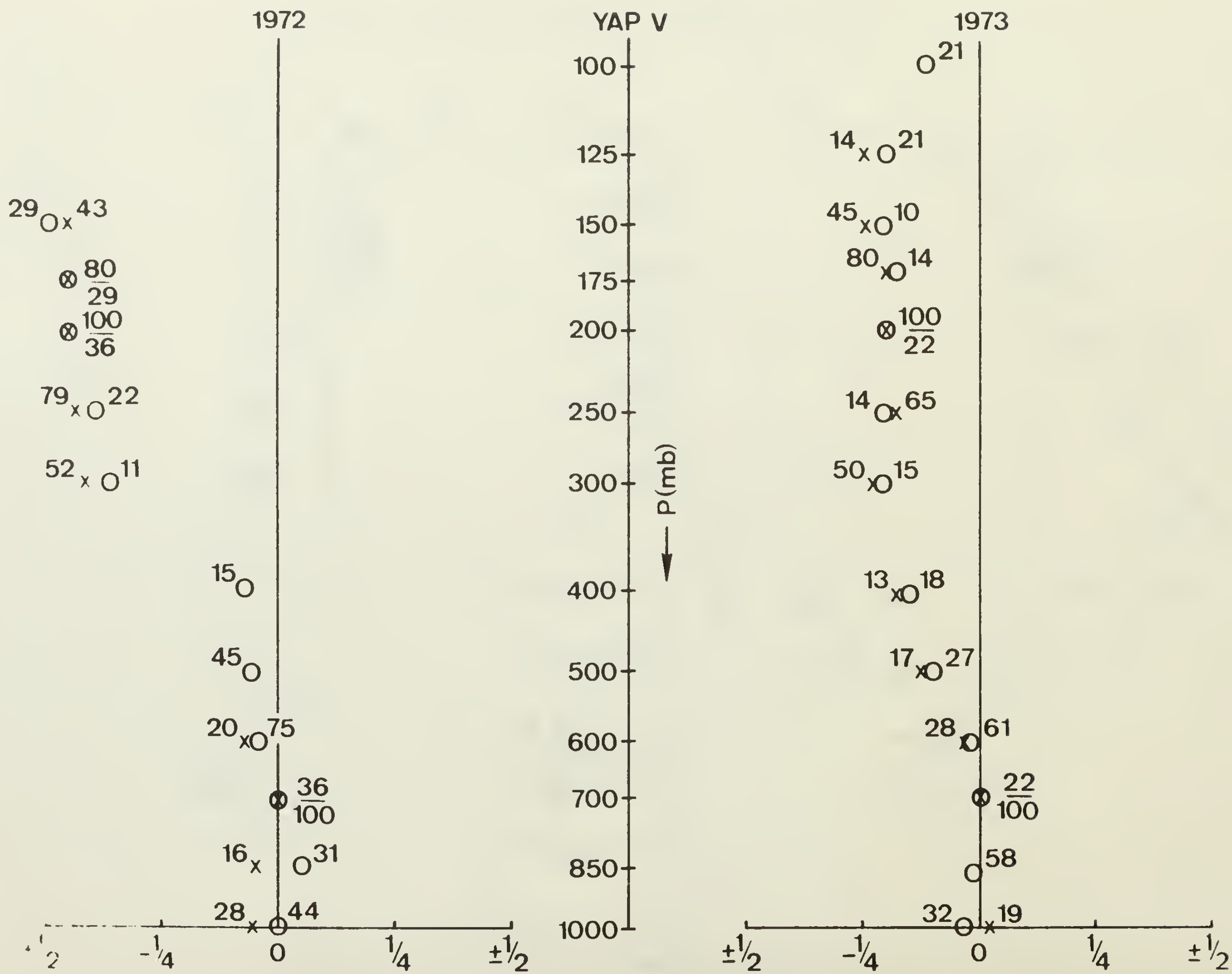

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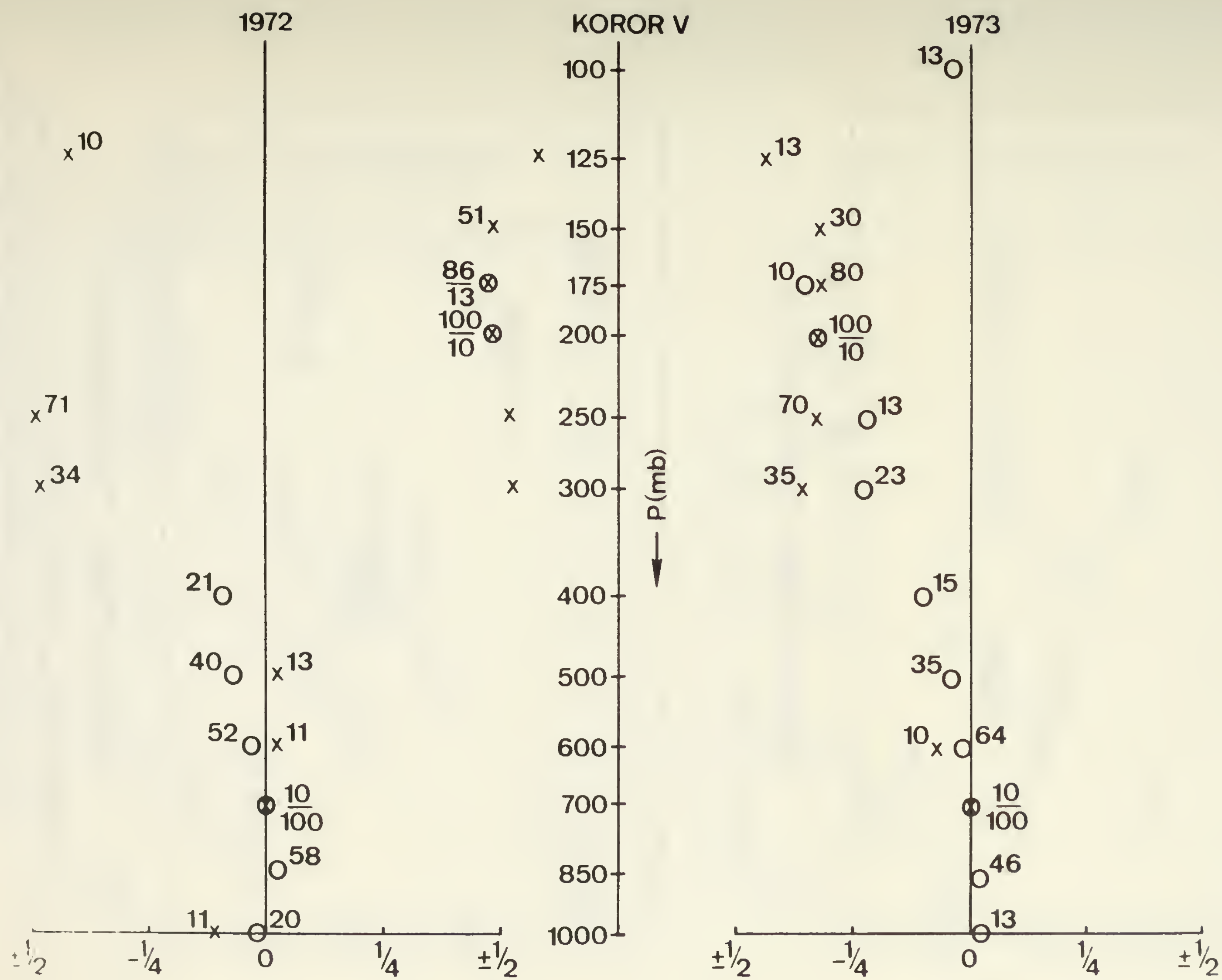

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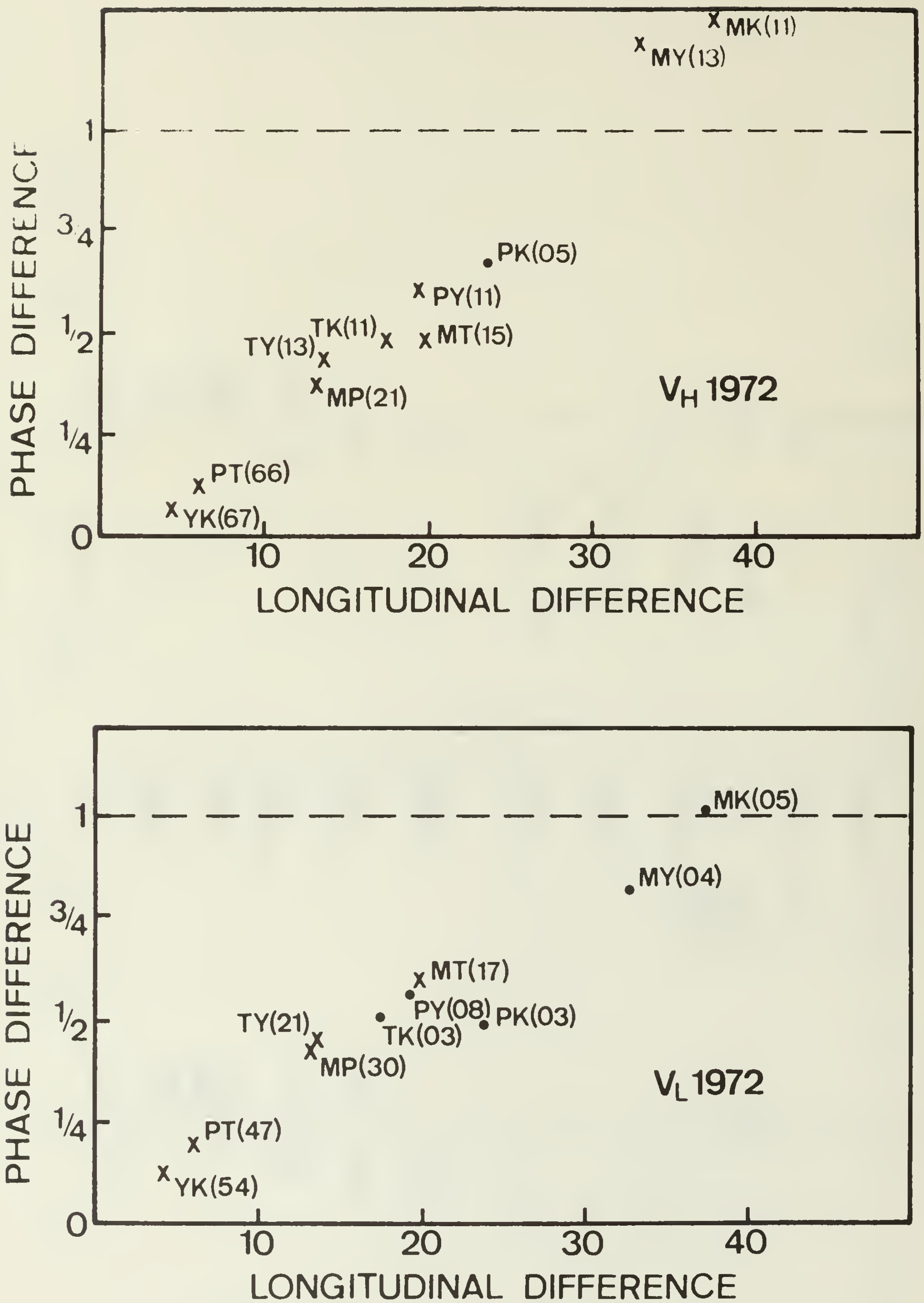

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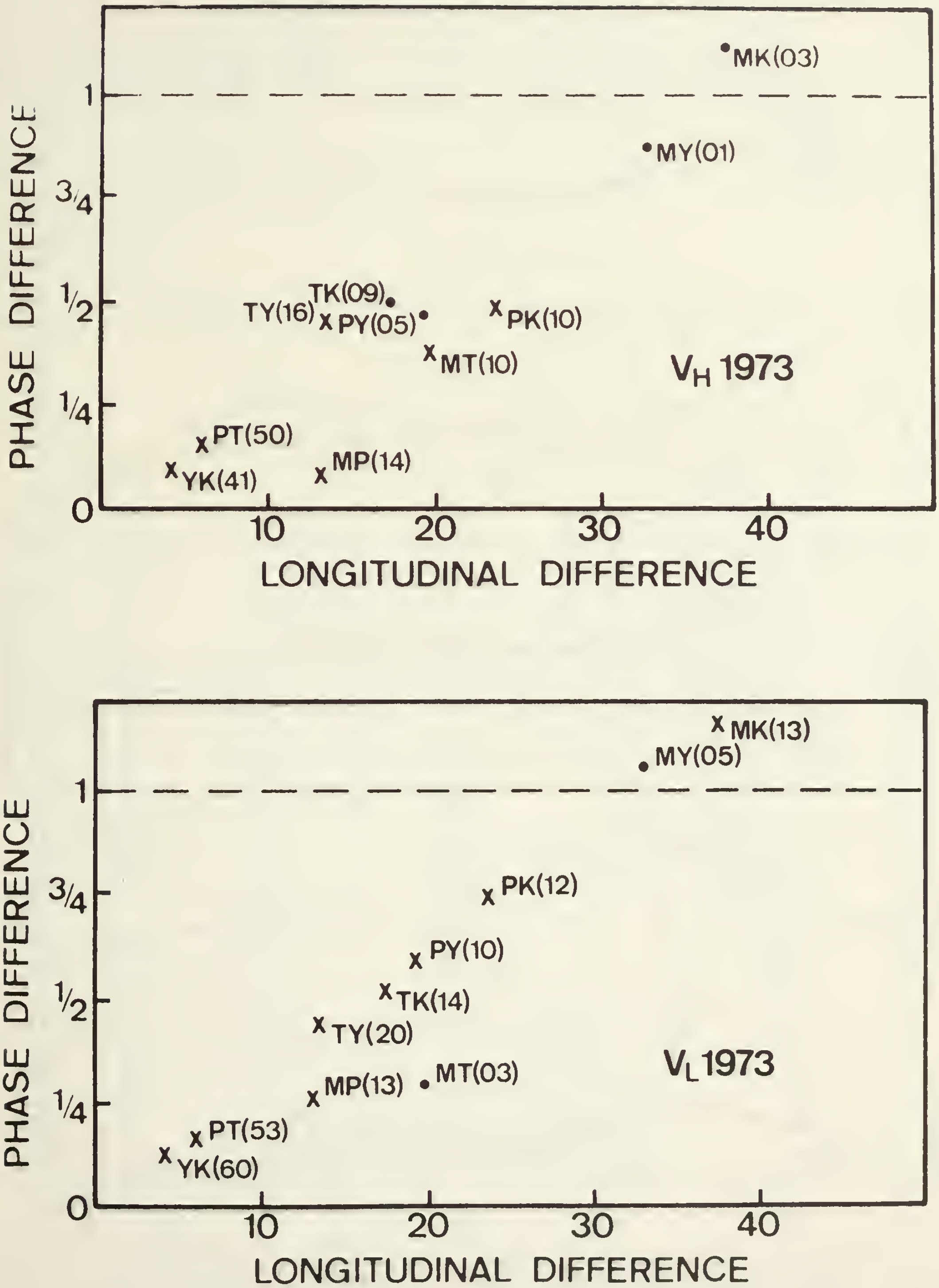

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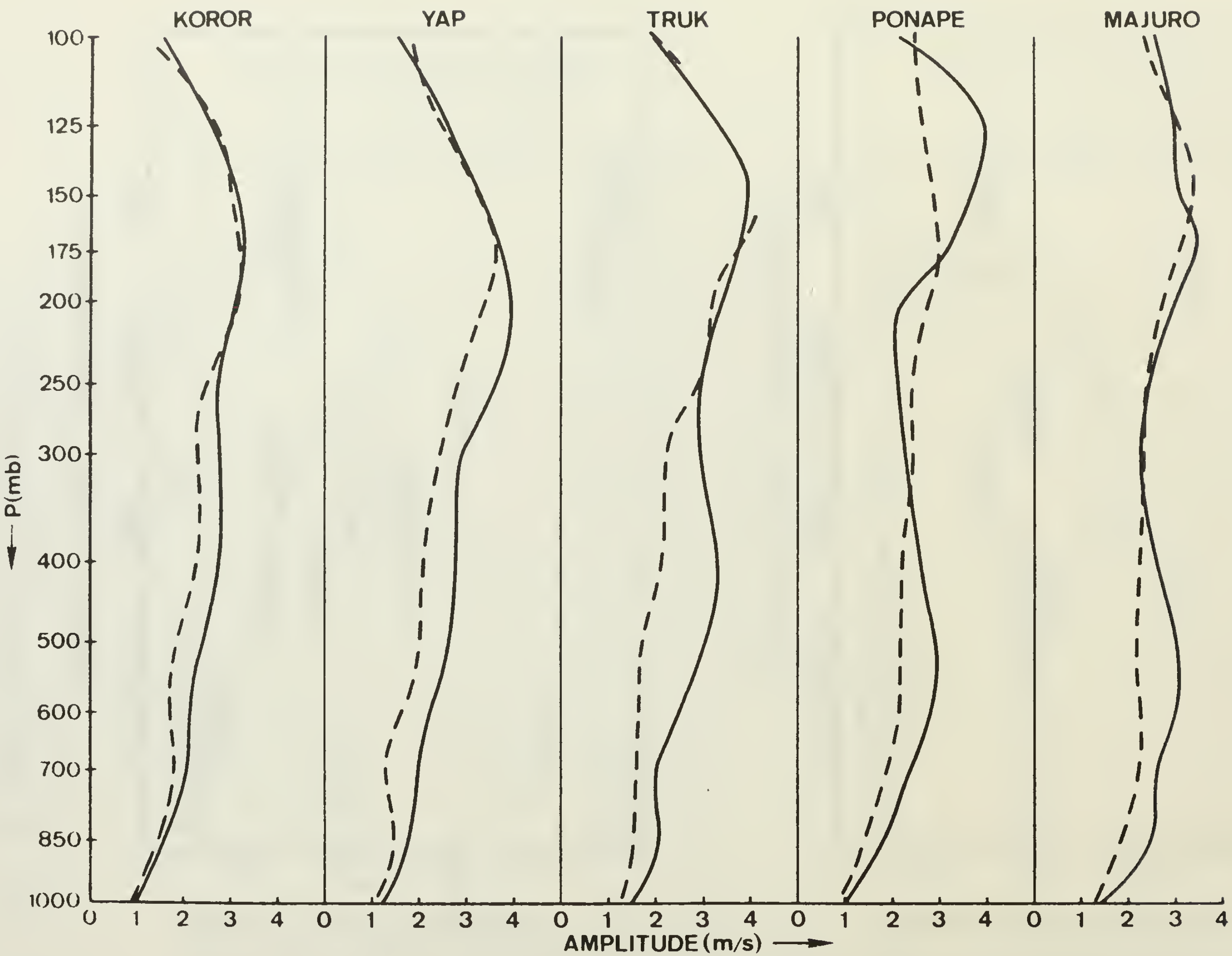

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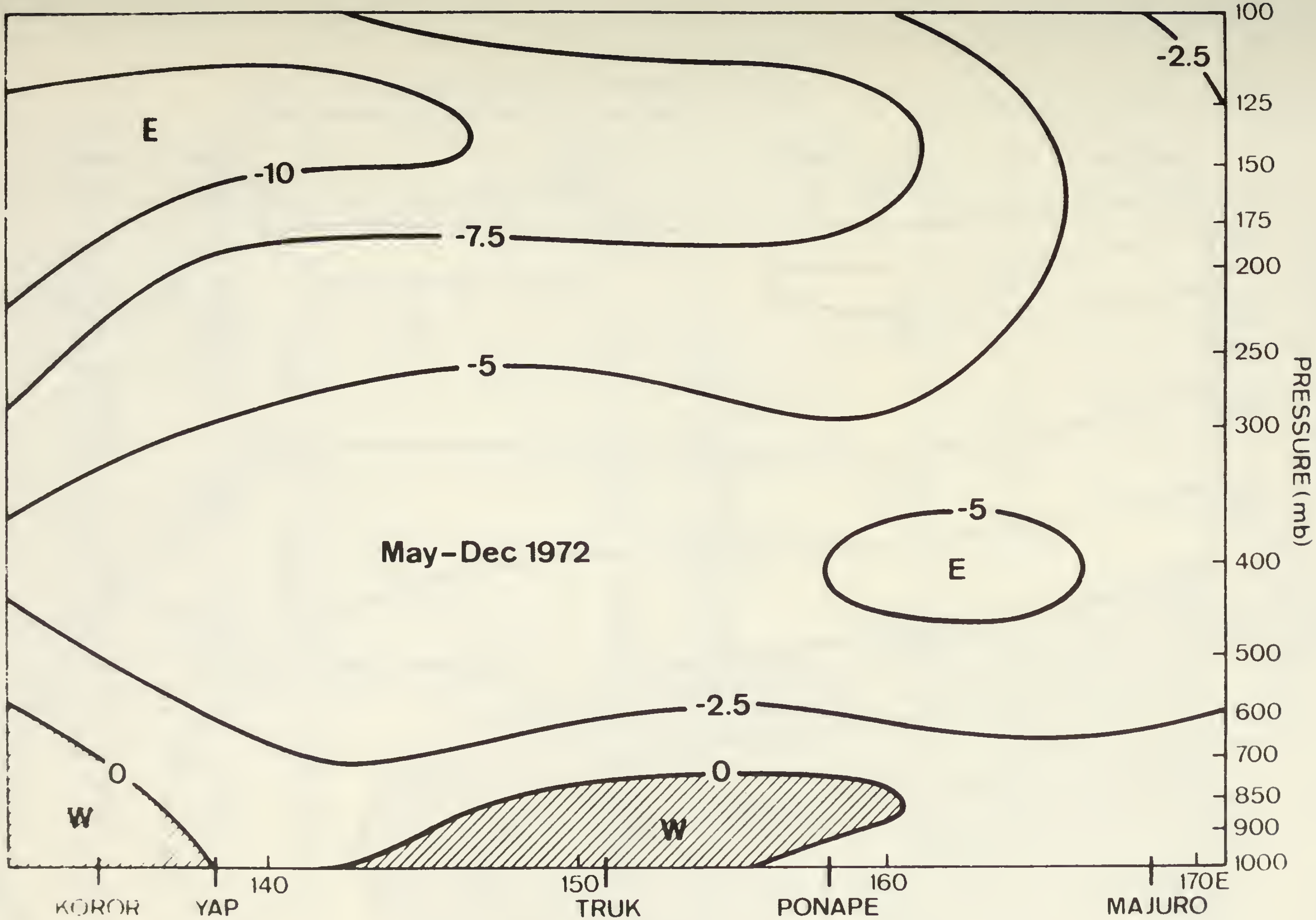

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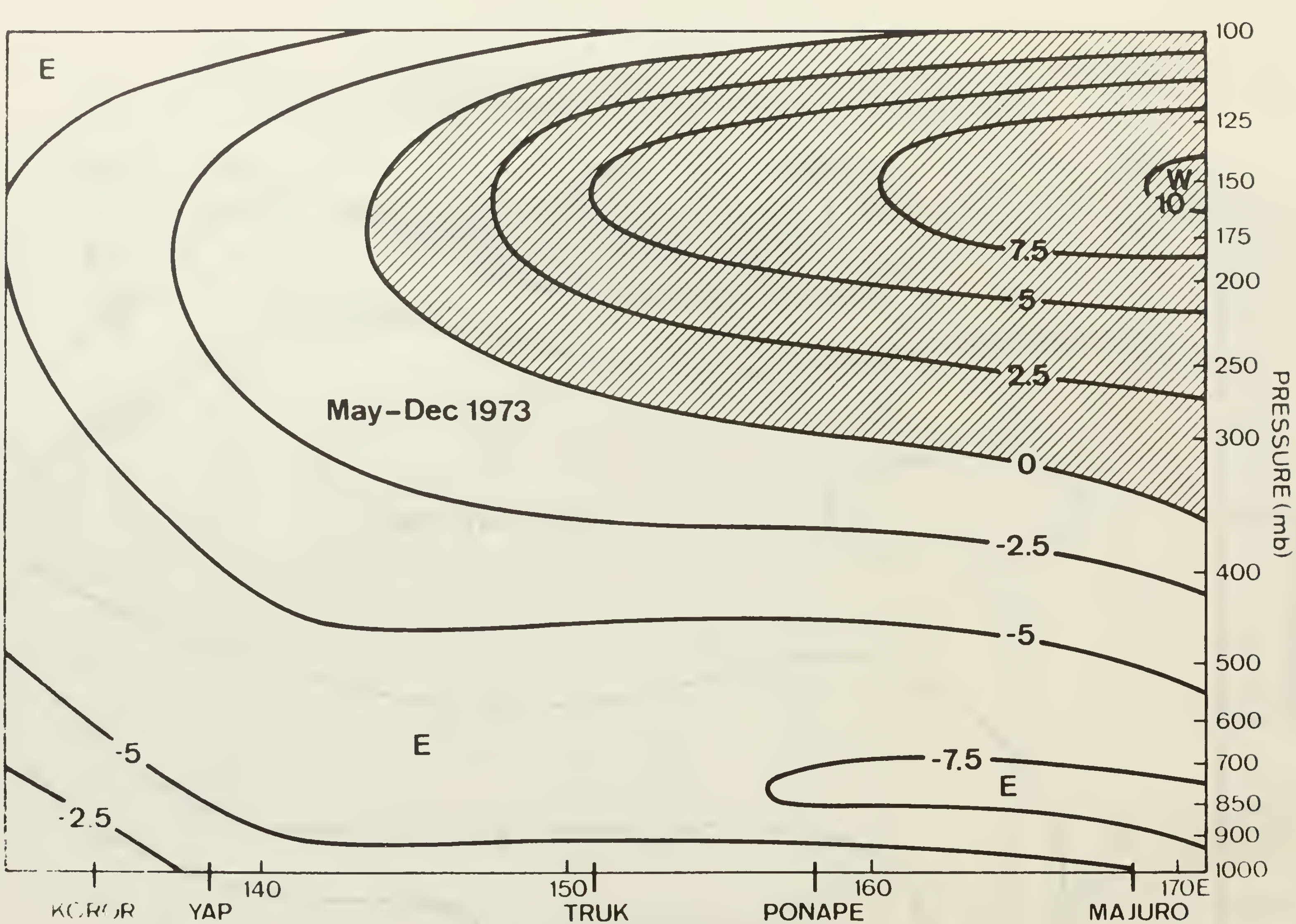

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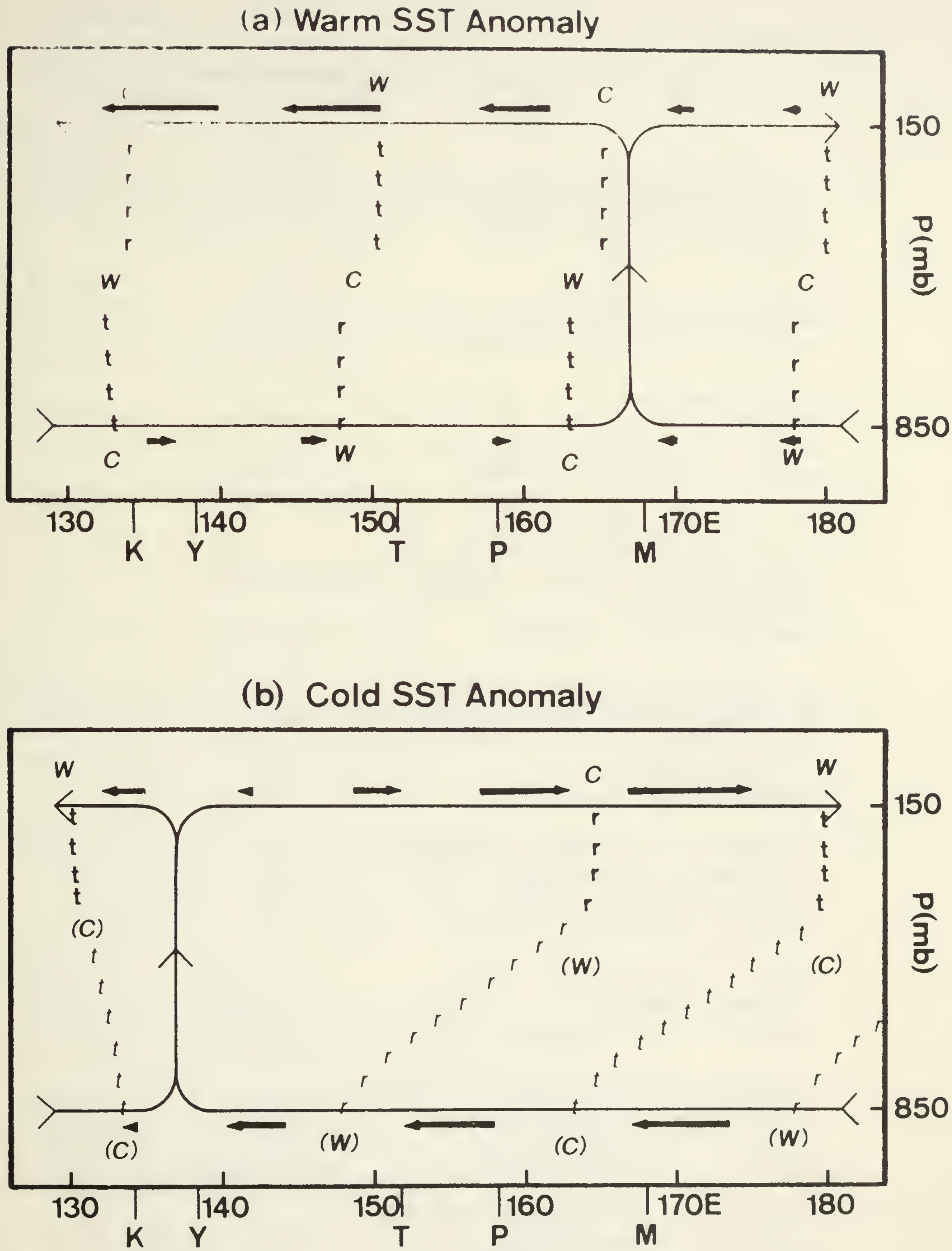

Fig. 15. Proposed model for the influence of sea-surface temperature variations on the 4-5 day wave structure. See text for details.

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